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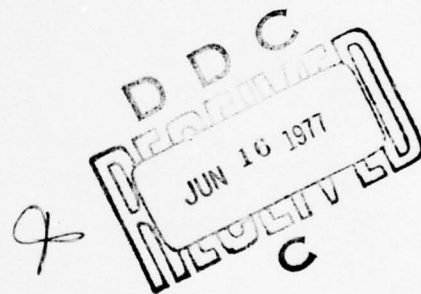
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A REVIEW OF THE LITERATURE ON THE LEGIBILITY
OF ALPHANUMERICS ON ELECTRONIC DISPLAYS

Andrew T. Buckler



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A REVIEW OF THE LITERATURE ON THE LEGIBILITY OF ALPHANUMERICS ON ELECTRONIC DISPLAYS

INTRODUCTION

The past 20 years have seen a tremendous surge in electro-optical technology. As a result, a lag has occurred between the availability of complex, electronically-generated display media and the research data required to guide designers in human factors considerations for these displays. Researchers have been forced to rely largely on either their own intuitions or on the principles which were derived from studies on non-electronic display media. Only recently have researchers begun to attack the problems created by this new technology. The purpose of this literature search is to assemble and summarize the data which have been gathered thus far, so that future research may be aimed at specific problems in the field rather than reproducing data which have previously been obtained and accepted.

For the parameters discussed, effort has been made to cite data which were obtained specifically with electronic display devices. This is in recognition of the differences between electronic and non-electronic display characteristics. For instance, electronic symbols are luminous while conventional symbols are usually illuminated; conventional display symbols are usually composed of solid, continuous strokes while electronic symbols are made up of closely spaced lines or dots. In several areas, however, electronic display data were found to be unavailable or inadequate. In these cases, data gathered on non-electronic display media must suffice.

This report will concentrate primarily on the *constructions and characteristics* of the alphanumerics themselves. Other variables, such as ambient illumination, vibration, display surface, while acknowledged to be important are beyond the scope of this review.

DISCUSSION

For purposes of this review, the term "electronic display" will refer primarily to the cathode ray tube (CRT) and solid-state dot-matrix displays. Legibility is operationally defined as a measure of the accuracy, speed, rate, and threshold of identification of alphanumeric symbols. The following parameters will be discussed:

- a. Generation technique
- b. Font
- c. Symbol subtense
- d. Resolution
- e. Percent active area
- f. Contrast

- g. Symbol-width-to-height
- h. Stroke-width-to-height
- i. Symbol spacing
- j. Viewing angle
- k. Edge displayed symbology
- l. Color

Generation Technique

Most of the research thus far has compared dot-matrix generation with symbols obtained through strokes of the electron beam (33,44,54,55,56). Dot matrices have been rated superior to stroke-written symbols in most studies (33,54,55). One researcher found strokes to be superior to dots under degraded conditions of overprinting which presents special problems for dot-matrix symbols (44). It is concluded that for most systems applications, dot matrix-symbology is superior to stroke-written.

The relative advantages of CRT versus dot-matrix-generation techniques are still in question. It is expected that each technique will be shown to be of value for specific applications. Research to investigate these differences is sorely needed.

Font

Font is the fundamental geometry or style of a set of alphanumeric characters. It is heavily influenced by generation technique, since symbol distortion may occur with low resolutions of some techniques, especially dot matrix. For dot-matrix displays, it has been noted that increased matrix size allows closer approximations of stroke-written fonts (7). It is recommended that font styles be kept clear and simple—no serifs, no variable stroke-widths, no slanting of characters and only uppercase letters (1,33,36,54, 55,56).

A large volume of data collected on non-electronic displays has produced several acceptable fonts, including Leroy, Lincoln/Mitre, NAMEL and Hazeltine, among others (10,17,23,24,35,38,39,47). The standard Leroy font is nearly identical to that specified by Military Specification MIL-M-18012 (29) (Figure 1). Several efforts have been made to improve on the Leroy font for electronic display applications (24,30,32,40,44,47,48). These studies for the most part point to the acceptability of the standard Leroy font for systems use. Some improvements may be possible to take advantage of specific display characteristics (21,27). Some proposed dot-matrix fonts are shown in Figure 2. However, maintenance of a uniform font throughout a particular aircrew station would be a desirable goal (53). This would point to the continued use of Leroy and MIL-M-18012 fonts for military applications.

A B C D
E F G H
I J K L
M N O P
Q R S T
U V W X
Y Z

0 1 2 3
4 5 6
7 8 9

Figure 1. Military standard MIL-M-18012 standard lettering font.



Figure 2. Comparison of Lincoln/Mitre symbols constructed from four dot matrices and solid strokes (from Shurtleff, 1970).

Symbol Subtense

In order to allow for differences in viewing distance, symbol height is usually described in terms of the angle subtended by the top and bottom of the symbol at the eye of the observer. This is known as the symbol subtense and is generally expressed in minutes of arc.

Many studies have investigated the effects of symbol subtense on legibility. Several researchers have noted the interaction of subtense with other symbol parameters, such as contrast, blur, and resolution (16, 20, 23, 33, 34, 38, 40, 47, 49, 53). Transilluminated symbols were found to require 16.8 minutes of arc under good conditions and 26.8 minutes if blurred (20).

For CRT and dot-matrix applications, resolution becomes an important factor in the determination of required symbol subtense. In general, as resolution improves the subtense required for good legibility is decreased (16, 23, 33, 34, 38, 47, 49). Resolution is usually expressed in terms of lines per symbol height (raster-type CRT) or matrix size (dot matrix). It is recommended that for systems applications, "symbol size" be described as subtense and resolution (23, 53). Research has shown that with resolution of six lines per symbol height, approximately 36 minutes of arc is required for good legibility (33, 47), while 8-12 lines require only 12-15 minutes (33, 34, 37, 38, 47, 49). As a general guide for systems design, it is recommended that symbol size be the greater of 15 minutes or 10 lines under conditions of good contrast, and 21-25 minutes or 16 lines with poor contrast (23, 53).

Resolution

As stated above, resolution is usually expressed in terms of lines per symbol height for raster-type CRT's and matrix size for dot-matrix displays. A large volume of research data is available on raster scan CRT's to determine acceptable ranges of resolution. These studies have shown that decrements begin to occur somewhere below 10 lines per symbol height, and that at six lines performance measures show significant declines (2, 13, 14, 19, 28, 33, 37, 47, 48, 49, 53). A minimum of about 10 lines per symbol height is recommended for systems applications (13, 23, 33, 37, 48, 53), although one researcher has found 15 lines to be optimal for classroom use (31). Resolution of 10 lines has also been found to be acceptable for displayed words (26). Scan line orientation has been shown to have no significant effect on legibility (45).

Research studies with dot-matrix displays have compared matrix sizes ranging from 3x5 to 15x21. The 3x5 matrix has been shown conclusively to be too small for systems use (41, 42). However, while some researchers have found no differences between 5x7, 7x9, and larger matrix sizes (40, 53), others have found the 7x9 to be significantly more legible than the 5x7 (36, 43, 54, 55, 56). For systems applications, matrix height of at least seven dots are recommended, although nine dots may be better, especially if symbols are subject to any degrading. A 15x21 matrix size is required as a minimum where symbols are to be rotated on the matrix (53).

Again, the interactions of resolution with other parameters in the display situation are noted. The values given above assume that symbol subtense is large enough to permit good legibility and that other parameters are not significantly degraded. Actual resolution requirements for a specific display use will depend on (1) type of symbology, (2) environmental conditions, (3) viewing distance, and (4) task requirements (33).

Percent Active Area

Percent active area is a concept which has arisen to describe the proportion of a symbol which is actually emitting light. It is defined as $\left(\frac{\text{Emitter size}}{\text{Emitter space}}\right)^2 \times 100$ (53). Percent active area can be increased by (1) increasing emitter size, or (2) decreasing spacing between elements, assuming subtense is held constant. It has been demonstrated with CRT displays that increased active versus inactive bandwidth results in improved legibility (4).

With dot-matrix displays, research has also found that decreasing the space between active elements results in improved legibility (8). Larger dimmer dots were found to give better legibility than smaller, brighter dots (15). It has been suggested that this is due to the fact that the larger dot size produces a greater area of retinal stimulation, thus causing the symbol to appear brighter to the observer (53).

Another approach has been to vary the shape of the dots to achieve maximum legibility. Square and circular dots have been found to be superior to rectangular and elongated dots respectively (8, 55, 56). The square and circular shapes result in smaller spaces between emitters. Several emitter shapes have been suggested as being worth further investigation, including circles, squares, hexagons, triangles, regularly spaced lines and staggered lines (33).

The important effect of high percent active area is to produce an illusion of continuity of symbol form. The emitters should be large enough and spaced close enough to avoid being perceived as separate, discrete units by an observer at normal viewing distances. The symbol should give the illusion of being composed of solid, continuous lines, since perception of raster line or dot structure tends to interfere with perception of fine detail of displayed information (3, 18, 53).

Contrast

Contrast may be represented by the ratio of the brightness of one object to that of another. For displays, symbol contrast usually refers to the ratio of brightness between the symbol and the display background. The polarity or direction of contrast refers to whether the symbol is light on a dark background or dark on a light background. Most researchers agree that direction of contrast does not have any significant effect on legibility except under degraded conditions (22, 23, 33, 37, 38, 46, 53). For most electronic systems applications, practicality would dictate light symbols on a dark background.

Required symbol-ground contrast ratios will depend on a number of factors such as display luminance, ambient illumination and reflective characteristics of display surface (50, 52). Recommended contrast levels range from 8.5:1 to 10:1 (8, 9, 50, 53). In general, higher contrast results in improved legibility, especially under high ambient illumination.

Another factor related to contrast is that of display luminance versus surround luminance. Since this is dependent on factors outside the display itself, it is discussed only briefly here. A display-surround contrast of no more than 2:1 is recommended to avoid viewer discomfort and adaptation problems (50).

Symbol-Width-to-Height Ratio

An optimum width-to-height ratio seems very difficult to pinpoint. A ratio of 3:4 was found to be of greatest legibility on non-electronic display media (51). Presently, values ranging from 1:2 to 1:1 are generally acceptable, since research has not narrowed down to an optimum value (33, 50). This does not appear to be a significant parameter, so long as values are maintained within this broad range.

Stroke-Width-to Height Ratio

Stroke-width-to-height ratios have primarily been investigated for non-electronic display media. Results have generally shown that stroke width has little effect on legibility except under degraded conditions (5, 6, 7, 11, 12, 25, 51). Stroke-width-to-height ratios ranging from 1:6 to 1:10 are recommended. Until data are accumulated on electronic displays, these values should be used as guidelines (33, 37, 50).

Symbol Spacing

Again, available data refer to non-electronic displays. A large range of spacing ratios seem to be acceptable. Symbol spacing 50 percent of letter width seems to be a middle value (11, 12), while values ranging from 25 percent to 200 percent have been shown to be acceptable (46). Extremely large values (over 100 percent) should be applied with caution however, especially if word information is to be presented. Symbol spacing values between 26 percent and 63 percent are recommended for electronic display applications until data are collected specifically for electronic displays (33).

Viewing Angle

Viewing angle describes how much the observer's line of sight differs from perpendicular to the display surface. Research has shown that performance decrements begin to occur somewhere between 19° and 38° from perpendicular for non-electronic displays (14, 24, 37). These findings would seem to apply for electronic displays with respect to the effects of foreshortening of character size. However, research is needed to determine the effects of loss of luminance due to display surface reflections (53). This effect is dependent on the characteristics of the specific device in use. For classroom use, a maximum viewing angle of 30° is recommended (31).

Edge Displayed Symbols

Research on CRT displays has shown that symbols displayed near the edge of the screen should be approximately 11 percent larger in visual subtense to maintain legibility (23, 33, 38, 47). This effect is due largely to the curvature of the CRT screen. With this curvature reduced or eliminated, as with a solid state dot matrix display, this effect would likely be lessened.

Color

Practical constraints dictate that most electronic displays be monochromatic. Minimum human sensitivity is to blue light which induces a kind of myopic reaction. Maximum sensitivity is to green-yellow light with red also showing high sensitivity (53). However, one researcher has found red to be more legible than green-yellow (14). An additional advantage of red light is its compatibility with dark adaptation. For monochromatic displays, color is not usually a significant factor so long as blue is avoided. Therefore, color should generally be chosen on the basis of display hardware characteristics (53). Research is needed to determine the effects that multichromatic displays will have on legibility and what color combinations will prove most useful.

SUMMARY AND CONCLUSIONS

Table 1 presents a summary of recommendations and guidelines based on the research reviewed. Two warnings should be issued to designers using these guidelines: (1) Since these are general statements describing minimum requirements, a good deal of flexibility should be allowed depending upon specific system characteristics, and (2) interactions among these parameters are complex, and if one parameter is allowed to vary from the recommended range, values for many of the other parameters should be adjusted accordingly. For instance, if resolution must be reduced below 10 lines per symbol height, legibility may be maintained by increasing subtense to 21-25 minutes. Each system will require its own combination of trade-offs among legibility parameters.

Legibility research has provided a firm base of data from which design principles and research questions may be derived for application to electronic display systems. One very important contribution of legibility research up to this time has been the identification of those parameters which significantly affect legibility and those which do not. For instance, research has shown that stroke width and symbol spacing may be varied over wide ranges with no significant loss of legibility, while relatively small variations in symbol subtense or resolution may have severe effects on legibility. Based on these results, it is recommended that designers concentrate on the following parameters for systems applications:

- a. Generation technique
- b. Symbol subtense
- c. Resolution
- d. Percent active area
- e. Contrast

Of course, the other factors discussed in this review should not be totally ignored. However, research has shown that a great degree of flexibility is allowable in those areas.

TABLE 1

Summary of Findings

Generation Technique	Dot matrix is rated better than stroke-written except under degraded conditions; Research comparing CRT with dot matrix is needed.
Font	Leroy or MIL-M-18012 fonts seem suitable for most applications; Some improvement may be possible for specific generation techniques.
Symbol Subtense	A minimum of 15 minutes is recommended under good conditions and 21-25 minutes under degraded conditions.
Resolution	For CRT's - a minimum of 10 lines per symbol height with good conditions and 16 lines with poor conditions; for dot matrix - a minimum matrix size of 7x9 is recommended for systems use.
Percent Active Area	Increased emitter size and decreased emitter spacing improve performance; Research is needed to determine optimal emitter shapes.
Contrast	Direction of contrast is insignificant except under badly degraded conditions; Symbol to ground contrast should be 10:1 or higher.
Symbol-Width-to-Height	Ratios ranging from 1:2 to 1:1 are acceptable.
Stroke-Width-to-Height	Acceptable ratios range from 1:6 to 1:10.
Symbol Spacing	Values between 26% and 63% of character width are recommended.
Viewing Angle	Decrements begin to occur between 190 and 380; Consideration should be given to the reflective characteristics of the display in use.
Edge Displayed Symbols	Should be 11% larger for CRT's.
Color	Not really significant for monochromatic displays, so long as blue is avoided; Research is needed for effects of multi-chromatic displays.

This review has found several areas where the literature is lacking and further research is needed:

a. What are the relative advantages and disadvantages of CRT versus solid-state dot-matrix display generation techniques?

b. Is there any way to overcome the problems arising from edge-displayed symbols and viewing angle?

c. Can an optimum size matrix be identified for dot-matrix displays?

d. What is the optimum value for percent active area?

e. What is the best emitter shape for dot-matrix displays?

f. Can the MIL-M-18012 and Leroy fonts be improved to take advantage of dot-matrix display characteristics?

g. What effects will multichromatic displays have on legibility? What color combinations will be most legible?

h. Can the relationship between contrast, resolution, subtense, and percent active area be quantified so that trade-offs can be worked out among these parameters? Some effort has already been made in this direction (53).

It is hoped that this review will be of some value in providing general guidelines to display systems designers and in providing researchers with a summary of previous research and some insights into which areas require further investigation.

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